PISM, a **P**arallel **I**ce **S**heet **M**odel: Current status of our Antarctic ice sheet simulation

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Outline

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Continuum model for multi-modal thermocoupled shallow flow

Verification

Results for Antarctica

Open source scientific computing and PISM

Equations and laws of the model: APPLIED EVERYWHERE

- map-plane conservation of mass
- 3D (shallow approximation of) conservation of energy including bulk strain heating
- 3D computation of age of ice
- 3D computation of grain size (using Vostok core relation between age and grain size; *EPICA 2004, Nature*)
- incompressibility
- computation of basal melt water from conservation of energy; freeze-on can occur
- earth deformation by method in (*Lingle and Clark 1985*) and (*Bueler and others, to appear Ann. Glaciol.*)

Equations and laws of the model: (FLOW MODE)-DEPENDENT

(i) in interior ice sheet we
- apply shallow ice approximation (SIA) determination of velocity
- use Goldsby-Kohlstedt (*2001; JGR*) flow law

(ii) in ice streams we
- apply shallow MacAyeal equations with either linear basal drag (*MacAyeal 1989*) or plastic till (*Joughin,MacAyeal,Tulaczyk 2004* and *Schoof 2006*) to determine velocity nonlocally
- use a Glen flow law ($n = 3$) with Paterson-Budd temperature dependence

(iii) ice shelves are ice streams *sans* basal drag!

What is *not* in the model

- full Stokes equations (i.e. without shallowness assumptions)
- polythermal ice
- an anisotropic flow law
- Goldsby-Kohlstedt in streams and shelves [this is from a *technical issue*: what is effective viscosity in G.-K.?]

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Verification for ice sheets

A DEFINITION:

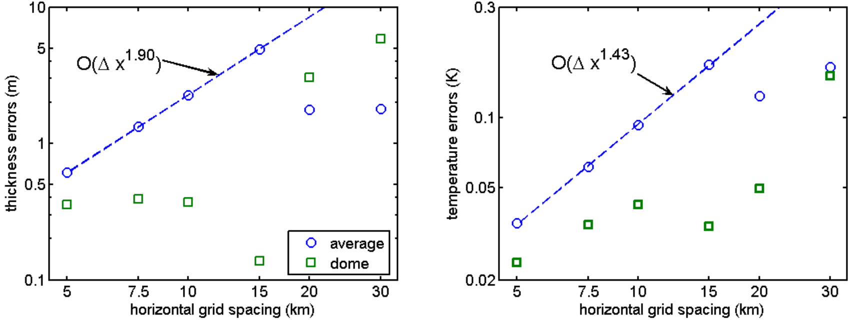
Verification is both measuring the difference between numerical results and exact solutions and measuring the rate at which numerics converge to continuum values as grid is refined.

Are there enough exact solutions? Perhaps so! There are:

- similarity solns to the isothermal SIA (*Halfar 1983*, *Bueler and others 2005*)
- "manufactured" solns to the isothermal and thermocoupled SIA (*Bueler and others 2005*, *Bueler and others, submitted*)
- an exact soln to the MacAyeal equations for ice streams with linear drag (*Brown UAF MS Thesis 2006*)
- an exact soln to the ice stream equations with plastic till (*Schoof 2006*)

Convergence under grid refinement: an example

We have verified our numerical scheme for the thermocoupled SIA in (*Bueler and others, submitted to J. Glaciol.*). Here are thickness errors (left) and temperature errors (right) relative to exact values:



Similar results apply for ice streams using the exact solutions from (*Brown UAF MS Thesis 2006*) and from (*Schoof 2006*).

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Inputs to model: Standard data sets

- accumulation from (*Vaughan et al. 1999*), provided by British Antarctic Survey (BAS)
- surface temperature from (*Comiso et al 2000*); BAS
- bed elevation is BEDMAP, from (*Lythe et al 2001*); BAS
- thickness is based on BEDMAP and surface elevations from (*Liu et al 1999*); BAS
- geothermal flux is from (*Shapiro and Ritzwoller 2004; Earth Planetary Sci. Let.*); we plan to compare to newer values from (*Fox Maule et al. 2005; Science*)
- balance velocity is used for flow mode "mask" (*Bamber et al 2000, based on Budd and Warner (1996) algorithm*); (next slide)

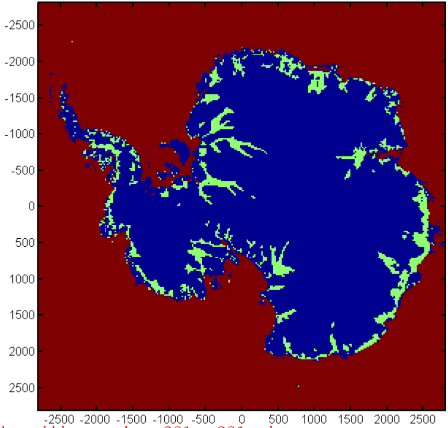
The which-type-of-flow mask

Flow mode is determined for current state of Antarctic sheet by:

(sliding velocity) =

(balance velocity) − (shear deformational velocity by G.-K. flow law)

- **green** (ice stream) if (sliding) $> 40\,\mathrm{m\,a}^{-1}$
- **blue** (interior; SIA) if (sliding) $\leq 40\,\mathrm{m\,a}^{-1}$
- **red** if ice is floating (or ice-free ocean)



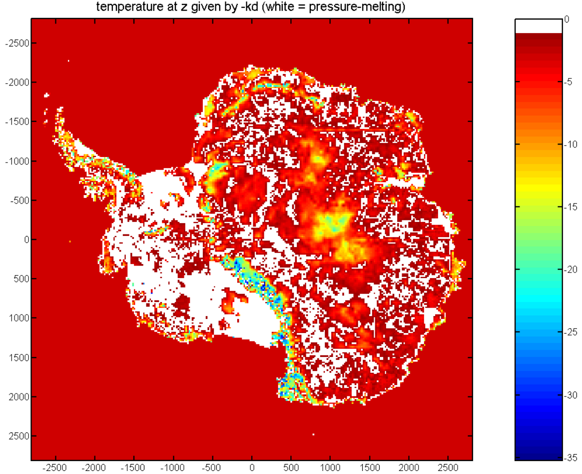
This figure and all results which follow are on 20km grid in map-plane; 281×281 points.

Initialization

- initializing a model for Antarctica *means solving obligatory inverse problems*
- there *are* good boundary data (surface elevation, accumulation, surface temperature, geothermal flux [*from other models*], . . .)
- while there are only very sparse data at depth (ice core data: temperature, age, grain size, . . .)
- we must "fill in" (guess) the following to initialize:
    - (i) temperature (long "spin-up" to meet advection time scale)
    - (ii) basal condition (i.e. drag coefficient or yield stress)
    - (iii) age and grain size (needed by G.-K. flow law)
    - (iv) melt/freeze rates under ice shelves
- *then* flow equations determine velocity field, but velocity field affects temperature . . . so one must evolve to equilibrium. . .

Modeled basal homologous temperature

(degrees C below pressure melting; white is at pressure-melting temperature)

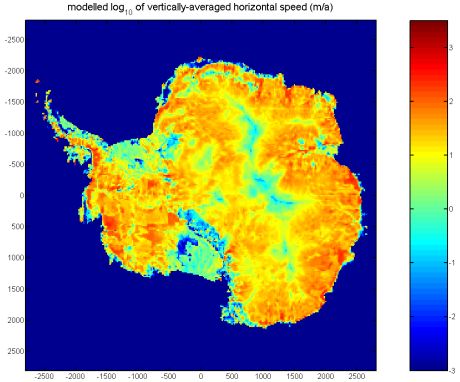


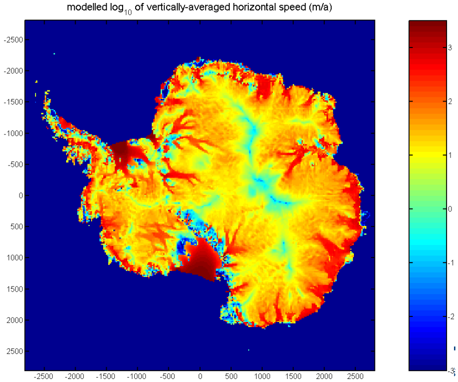
Result of 153k years evolution *fixing* current geometry but allowing temperature and velocities to equilibriate using SIA with Goldsby-Kohlstedt flow law.

Two kinds of models: SIA only and multi-modal

Figures both show $\log_{10}$ of *modeled* vert.-averaged horizontal speed. (Both computed by PISM on 20 km grid.)

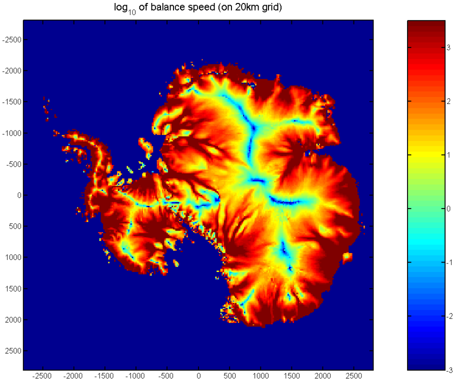
- left: SIA only (with Goldsby-Kohlstedt)
- right: multi-modal (SIA for interior, MacAyeal-Morland equations for ice streams and ice shelves)

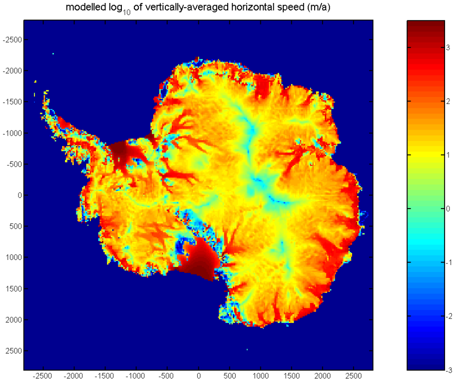




Balance velocities versus multi-modal PISM model

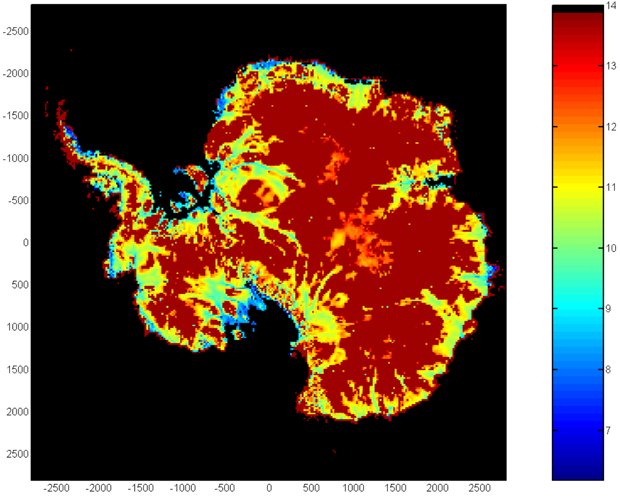
- left: $\log_{10}$ of balance speed (Bamber et al 2000)
- right: $\log_{10}$ of vert.-averaged horizontal speed (modeled; on 20km grid)





Estimation of basal drag assuming linear law

$\log_{10}(\beta)$ where β is in units $\mathrm{Pa\,s\,m^{-1}}$. (*Compare constant value* 2.0×10^9 *Pa s m*$^{-1}$ *in (Hulbe and MacAyeal 1998).*)



How the last slide was created

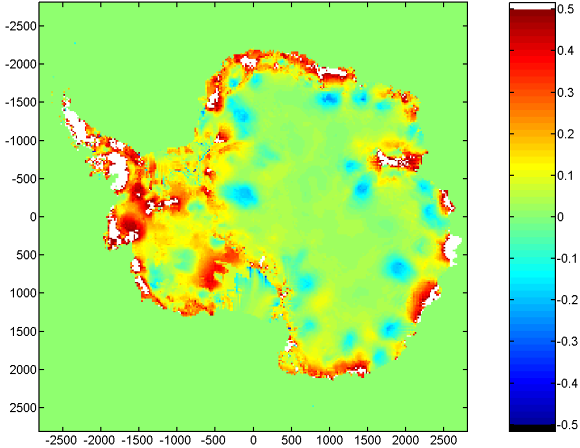
Getting basal drag from balance velocities using PISM:

1. shear deformational (SIA) velocities are computed at all grounded points (using Goldsby-Kohlstedt)
2. average deformational velocity is subtracted from balance velocity to give a sliding velocity
3. this sliding velocity is put into the MacAyeal eqns at all grounded points to determine the drag coefficient β which gives that much sliding

Note that if shear deformational velocities exceed balance velocities then get negative drag; we set $\beta = 10^{14}\,\mathrm{Pa\,s}\,m^{-1}$ in that case.

Modeled thickening rate from 900-year multi-modal (preliminary) run

Figure shows modeled $d(\text{thickness})/dt$ for 900 years of multi-modal evolution of geometry and 3D velocity fields; units are m/yr. (Temperature field fixed for this run.)



Conclusions from this 900-year run

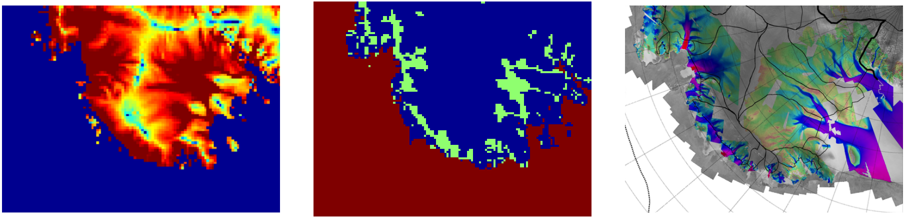
1. This is a first cut. The model is not tuned in any way to the present ice sheet.
2. There is volume loss in the interior but dominant effect is volume gain caused by thickening near the margins; can be tuned away.
3. This 900 year run gave average volume gain of $1453\,(\text{km}^3/\text{yr})$ during the run.
4. Volume loss/gain of plus or minus 1000 in units km^3/a is nonetheless "in the right ballpark." Compare GRACE value of $-152 \pm 80\,\text{km}^3/\text{a}$ for 2002–2005 (i.e. water-equivalent mass loss; Velicogna and Wahr, 2006).
5. We expect much better simulation of the present Antarctic ice sheet from PISM shortly.

PISM's flow model of streams and shelves

- PISM runs stably with surface evolving by mass continuity equation and with multi-modal velocity computation (sheet, stream, shelf).
- PISM can model both linear sliding under streams and a purely-plastic model for till deformation (Schoof 2006).
- Our current Antarctica runs use the balance velocities to determine the extent of the ice streams.
- Runs based on balance velocities tend to thin the ice shelves; they are *starved* for input.
- With observed surface velocities we will determine better geometry for ice streams and get better results for shelves too.

Why are the modeled ice shelves *starved*?

- left: detail of $\log_{10}$ of 20km-gridded balance speed (Bamber et al 2000)
- middle: detail of flow mode mask, derived from balance speeds and estimate of shear deformation (see model *initialization* above)
- right: *compare* detail of mosaic of speckle-tracking derived surface speeds (thanks Eric Rignot; see Joughin 2002 for method)



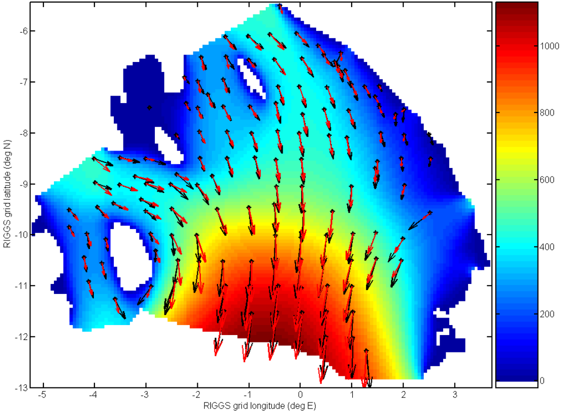
Note two problems with 20km gridded balance velocities:

- narrow ice stream outlets not resolved
- ice streams mislocated

Can improved resolution alone fix this? YES.

Example: Color shows modeled speed on Ross Ice Shelf with 6.8 km grid; 3 times finer than 20km above.

- **black** arrows are observed velocities (RIGGS)
- **red** arrows are PISM-modeled velocities at same points.



A 6.8 km grid is fine enough to resolve ice stream and glacier inputs to shelf. *Our solution of the ice shelf velocity equations then produces good modeled velocities.*

Data sets that NASA could obtain to aid ice sheet modeling

- 3-D temperatures at depth (appears possible with bistatic SARs, i.e. radar—P. Gogineni, pers. comm.)
- basal conditions
- accurate elevation rates over ice sheets with (e.g.) ICESat follow-on altimeters; CRYOSAT-2 and follow-on altimeters may be sufficient
- an improved thickness map
- an improved accumulation map
- surface velocity coverage south of 82 degrees
- ALSO: Computing power to do 10km and even 5km grid computations(!). We think PISM can do 5km grid computations with a few hundred processors and some performance tuning.

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PISM = Parallel Ice Sheet Model is open source

- the source code is licensed under the "GNU Public License"
- get latest complete source code from

  https://gna.org/projects/pism
- instructions for installation and running are at

  www.dms.uaf.edu/∼bueler/PISMdocinstall.htm
- more information (especially on verification and math) at

  www.dms.uaf.edu/∼bueler/iceflowpage.htm

Scientific computing considerations

- PISM uses PETSc (= Portable Extensible Toolkit for Scientific computing; by Argonne National Laboratory)
- PETSc automates distribution of finite difference computation over many processors
- PETSc also solves big matrix problems in parallel; *very useful in solving MacAyeal-Morland equations for streams/shelves!*
- PISM constructed with *modern tools*: object-oriented features of C++, version control using Subversion, etc.
- it is nice to have a supercomputer center at UAF (`www.arsc.edu`), but we've learned one still needs *one's own* fast multiprocessor computer for development!